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Water management for sugarcane and corn under future climate scenarios in Brazil

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ABSTRACT

Over the last several decades, there have been concerns worldwide about energy demand. Several alternatives to oil have emerged, among them the use of plant biomass for fuel. Sugarcane (*Saccharum spp* L.) and corn (*Zea mays* L.) have exhibited excellent potential in this regard. These crops are highly efficient in producing carbohydrates which can easily be fermented to produce ethanol. Proper irrigation practices, providing the ideal amount of water that the plant needs to reach its full potential yield, are needed to maximize income from these crops. Sugarcane and corn are of great economic importance to the state of São Paulo, where it is common to irrigate these crops. This research aims to determine conditions for increased productivity and water availability for these crops in the region of Piracicaba, SP, under future climate scenarios. To achieve this goal, two crop simulation models presented in DSSAT (Decision Support System for Agrotechnology Transfer), DSSAT/CANEGRO and CERES-MAIZE, were coupled with the MarkSim model for estimating data for current and future (1982–2012 and 2062–2092, respectively) climate scenarios. Information from the Intergovernmental Panel on Climate Change (IPCC) was used to generate data for current conditions, as well as future conditions: the A1B – a middle-term scenario which there are a fast economic growth and balance in the use of sources of fossil and non-fossil fuels; the A2 – a pessimistic scenario which there are a heterogeneous world and an oriented regional economic world; and the B1 – a optimistic scenario which there are local solutions to economic, social and environmental sustainability. Based on these results, for future scenarios, sugarcane cultivar RB86-7515 yield will be reduced by approximately 40% if the cultivars are not genetically improved. To maintain the same yield levels of hybrid corn BR201, these will be necessary to increase irrigation water by 81%.

1. Introduction

The cultivation of sugarcane (*Saccharum officinarum*) is of great importance for the Brazilian economy, contributing extensively to foreign exchange generation. This contribution is predicated on the many uses for sugarcane; it can be enjoyed fresh or used for fodder in animal feed or to produce sugar, ethanol, energy, brandy, brown sugar or molasses. It is currently cultivated on approximately 8.6 million hectares in Brazil, with an average yield of 70 t ha^{-1}, producing a total production of about 596 million tons year^{-1} (COMPANHIA NACIONAL DE ABASTECIMENTO – CONAB, 2013a,b). It is cultivated in the states of São Paulo, Goiás, Minas Gerais, Paraná, Mato Grosso do Sul, Alagoas and Pernambuco. São Paulo, with an area of 4.5 million hectares, is the largest producer. On average, 50% of Brazilian sugarcane production is converted into alcohol and 40% to sugar (CONAB, 2013a,b).

Corn (*Zea mays*) is one of the main cereals grown more around the world, providing widely used products for human and animal consumption, and raw materials for industry. This can be attributed mainly to the amount and nature of the accumulated energy reserves stored in the corn. Because of its many uses, corn is of significant socio-economic value, in addition to being an essential raw material for various agro-industrial complexes (Fancelli and Dourado-Neto, 2000). Currently, corn is grown on 14.7 million hectares in Brazil, with an average yield of 4.9 t ha^{-1}, resulting in a total annual crop of slightly more than 72 million tons year^{-1} (CONAB, 2013a,b). In Brazil corn is grown in Paraná, Mato Grosso, Goiás, Minas Gerais, Mato Grosso do Sul, Sao Paulo and Rio Grande do Sul, with nearly 17 million tons year^{-1} in Paraná, the state with the largest production (CONAB, 2013a,b).

According to Doorembos and Kassam (1979), the water requirement of sugarcane is 1500–2500 mm per season and irrigation management should be based on recommended allowable water deficit in the soil during each period of the phenological cycle. Souza et al. (1999), using

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a cannon type sprinkler irrigation system, obtained maximum stalk yields of 155.8, 126.9 and 141.9 t ha^{-1} for the RB72-454, RB76-418, and SP70-1011 varieties, respectively, with 13 months water application depths of 1.568, 1.424 and 1.589 mm, respectively. Daily sugarcane water consumption in the main producing areas of the country varies from 2 to 6 mm day^{-1}, depending on variety, the stage of crop development, and evapotranspirative demand. In general, the crop requires 250 mL of water to form 1 g dry matter (Bernardo et al., 2006). Corn requires 500–800 mm of water, depending on climate, for good production in one season (Doorembos and Kassam, 1979). Wilson and Shaw (1977) analyzing the results obtained by different authors found that the seasonal consumptive water use for corn ranged from 410 to 610 mm, while Fancelli (1991) reports a minimum water requirement of 300–350 mm for satisfactory non-irrigated production, if the available water is evenly distributed over the crop cycle.

Corn grown for the production of dried grains consumes 400–700 mm of water on average during the entire growth cycle, depending on weather conditions (Resende et al., 2003). During the early vegetative stages of growth in mild climates, consumptive water use does not exceed 2.5 mm day $^{-1}$. However, water use rises to 6.5–7.5 mm day $^{-1}$ during flowering and fruiting.

Crop growth simulation models facilitate the evaluation of agricultural production under a range of possible environmental conditions. The simulation of production under several different scenarios allows the producer to determine the best crops/varieties, and management practices, to reduce losses due to adverse growing conditions.

The Decision Support System for Agrotechnology Transfer (DSSAT) simulates growth and development of crops over time, considering climate, soil, management and genetic aspects of culture. It also assists in data organization (Jones et al., 2003). For sugarcane production system, the routine uses the DSSAT/CANEGRO model (Inman-Bamber, 1991; Singels et al., 2008). It is based on the CERES-MAIZE model (Jones et al., 1986) and developed in South Africa in order to model the most relevant physiological processes of the South African sugar industry (Inman-Bamber, 1991).

The CERES-MAIZE model, according to Jones et al. (1986), is able to predict details of phenological stages and number of corn leaves in six stages: P1 − emergency thermal time until the end of the juvenile phase (°C day); P2 − extension of the development delay for each hour of increment in the photoperiod above which the development proceeds at the maximum rate (h); P5 − thermal time between female flowering and physiological maturity (°C day); G2 − maximum number of grains per plant; G3 − grain filling rate during linear phase under optimum conditions (mg day^{-1}) and PHY − interval corresponding to the phyllochron between the appearance of subsequent leaves. Sensitivity to photoperiod and high temperature effects on the final number of leaves are considered. Furthermore, the three stages of vegetative growth, leaf initiation and leaf primordia appearance of initiation of flowering male, can be independently tested (Kiniry, 1991).

The CERES-MAIZE model is grouped in a Decision Support System for Agrotechnology Transfer (DSSAT) and has been widely used around the world. It considers water balance processes in the soil, radiation interception by the canopy, dry matter production and biomass partition (Kiniry et al., 1997). Version 3.1 provides information on the spatial performance of simulations and analysis of the results (Thornton et al., 1997).

Climate change may have a significant impact on the world economy in the twenty-first century (Houghton, 1996), affecting all economic sectors to a certain degree. Agricultural production, however, is the most sensitive and vulnerable sector, since the weather is a determining factor in crop productivity (Watson et al., 1996). Marin et al. (2007) reported that the simulation of future scenarios is useful to quantify the vulnerability of the productive sectors and to plan actions according to these new conditions.

According to Pachauri and Reisinger (2007), the recent estimates of temperature will rise around the range of 1.8–3.6 °C. The CO_2 concentration will increase around 720 ppm in 2090–2099, depending on the scenario of greenhouse gases emissions considered in the climate models. Marin and Nassif (2013) showed that the increase in temperature and concentration of CO_2 for sugarcane is good to soil-plant-atmosphere connection increasing the sugarcane productivity. Yield and irrigation will decrease in corn while the crop will suffer water stress (Minuzzi and Lopes, 2015).

MarkSim® is a model that has been used along with DSSAT to simulate future scenarios. It is a third-order Markov precipitation generator (Jones and Thornton, 1993, 1997, 1999, 2000; Jones et al., 2002), which was developed more than 20 years ago. MarkSim is essentially a daily rain simulator that uses a third-order Markov chain process to predict the occurrence of a rainy day. It supplies weather data, based on geographical position, for the A1B, A2 and B1 climate change scenarios, in the formats used by DSSAT. For a specified geographical position, MarkSim model uses current weather data, along with Intergovernmental Panel on Climate Change (IPCC) projections, to generate weather data for future years. Currently, it supplies weather projections up to 2095.

The main objective of this study was to compare sugarcane and corn response to different levels of irrigation for Piracicaba, SP, Brazil, by applying the DSSAT/CANEGRO and CERES-MAIZE models, with future weather scenarios, simulated by the MarkSim model.

2. Material and methods

The research was conducted at the Department of Biosystems Engineering, College of Agriculture “Luiz de Queiroz”, ESALQ/USP, located in Piracicaba, SP, with CWa climate according to the Köppen classification, (22° 43 ‘33 “of south latitude and 47° 38 ‘00 “W, with 546 m height). The research was conducted in three distinct stages:

1. Developing an understanding of DSSAT 4.6, specifically the models CANEGRO and CERES-MAIZE and using/developing a climate and edaphic database for the city of Piracicaba, SP for sugarcane and corn;
2. Understanding future scenarios and projections of the IPCC (Intergovernmental Panel Climate Changes) and using MarkSim to simulate different scenarios of climate change, and
3. Performing statistical analysis for the two crops (sugarcane and corn) to characterize their simulated responses (using DSSAT/CANEGRO and CERES-MAIZE) to irrigation management under current conditions (1982–2012) and under projected climate scenarios (2062–2092).

Climatic data for 31 years (1982–2012) were obtained from a database for a conventional weather station located on top of the College of Agriculture “Luiz de Queiroz”, USP, in Piracicaba, SP. These daily data − solar radiation MJ m^{-2} day^{-1}, maximum and minimum air temperatures (°C), relative humidity (%), precipitation (mm) and wind velocity (m s^{-1}) − were used to estimate the potential evapotranspiration based on the Penman-Monteith equation (Eq. (1)), the water deficit for the crop, and the potential and current yields of sugarcane and corn.

$$ETo = \frac{0.408\Delta\left[(Rn - G) + \gamma\frac{900}{Ta+273}u_2(e_s - e_a)\right]}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

Where, ETo is the reference evapotranspiration (mm d^{-1}), Rn is the net radiation (MJ m^{-2} d^{-1}), G is the soil heat flux (MJ m^{-2} d^{-1}), (es − ea) represents the vapor pressure deficit of the air (kPa), γ is the psychrometric constant (kPa °C^{-1}),u_2 is the wind velocity (m s^{-1}) and Ta is the average air temperature (°C). DSSAT 4.6 has an interface called weatherman which generate reference evapotranspiration data according to Eq. (1).

The soil in this research was an Oxisol with 1.2 m depth, situated in

Table 1
Average and variation coefficient of meteorological data for thirty one years (1982–2012): global radiation, maximum temperature, minimum temperature and rain.

current	G Rad (MJ m^{-2} day^{-1})		Tmax (°C)		Tmin (°C)		Rain (mm)	
	average	cv (%)	average	cv (%)	average	cv (%)	average	cv (%)
Jan	18.40	14.14	30.40	3.80	19.51	3.73	243.65	37.49
Feb	18.92	16.64	31.02	3.87	19.48	3.47	180.53	51.04
Mar	17.24	13.92	30.41	3.50	18.63	3.35	168.85	48.47
Apr	16.05	12.24	29.12	3.29	16.52	5.66	78.28	65.37
May	13.38	13.97	26.13	3.74	13.14	12.93	74.60	86.72
Jun	12.34	13.48	25.41	5.40	11.06	12.89	46.98	107.04
Jul	13.49	16.49	25.72	4.60	10.69	13.39	33.93	116.65
Aug	15.95	16.83	27.69	4.58	11.95	12.30	30.71	113.56
Sep	16.52	16.48	28.19	6.52	14.43	9.02	63.78	77.06
Oct	18.74	14.15	29.82	5.48	16.55	7.08	114.02	59.25
Nov	20.17	11.46	30.30	3.25	17.67	5.84	139.11	48.47
Dec	19.60	11.75	30.29	3.12	18.87	4.61	189.99	30.21

experimental field of the Biosystems Engineering Department of "Luiz de Queiroz" College of Agriculture.

The soil data necessary to the model are: clay (61%), silt (17%) and sand (21%) content, color (red), drainage (well drained), runoff (moderately low), slope (12%), depth, carbon (1.4%) and nitrogen (0.1%) content, exchange cations capacity (ECC = 100 mmolc kg^{-1}) and water pH (5.0).

Both DSSAT/Canegro and CERES-MAIZE use water balance as input data based on crop growth modeling processes. Growth and development of sugarcane and corn, phenology, canopy development and biomass accumulation are the output of these two models (Singels et al., 2008).

The DSSAT/CANEGRO and the CERES-MAIZE models were calibrated to improve their performances. DSSAT/CANEGRO was calibrated and parameterized for the specific variety of sugarcane chosen for this study, RB86-7515, by Nassif et al. (2012). The authors found 0.98 for R^2 (determination coefficient), 0.82 for D (Wilmott index) and 0.59 for RMSE (Root mean square deviation). Besides that, the authors found CANEGRO, parametrized for RB 86-7515 variety, presented dry matter data very close to observed data with R^2 = 0.6, D = 0.6 and RMSE = 9.56. In all, there are 74 parameters: 31 related to ecotype, 20 related to cultivar, and 23 related to species. The plant life cycle averages 530 days, close to a year and a half. CERES-MAIZE was calibrated for the BR201 variety, for the genetic coefficients P1, P2 and P5 defining the phenology, G2 and G3 related to grain development by Gedanken et al. (1998) and PHY define by Hoogenboom et. al (1994). The authors found 0.95 for R^2(determination coefficient), 0.74 for D (Wilmott index) and 0.62 for RMSE (Root mean square deviation). The plant life cycle averages 120 days, almost 4 months. The planting season was April for sugarcane and February for corn.

The crucial point for the efficiency of the MarkSim model in simulating the current precipitation variance observed in both tropical and temperate regions is its innovative way of using re-sampling the Markov process parameters. To do this, a correlation matrix of twelve baseline probabilities, twelve monthly baseline transfer probabilities (i.e., the probability of a rainy day and three consecutive dry days) and the probability coefficients related to the effect of each of the previous three days were used. MarkSim offers weather data in the exact form DSSAT can read, with the most common and easy to use program units.

The A1b, A2 and B1 scenarios of IPCC, to be defined below, were then obtained and only the geographical position of the locality was used in the models. Based on the geographic position of the locality, the MarkSim model uses the current climatic data of the region and from the projections of the IPCC, generates climatic data for future years. The carbon dioxide was established in 720 ppm as in IPCC Fourth Report (2007).

Three scenarios from the IPCC 2007 fourth assessment report, A1B, A2 and B1 were simulated with the MarkSim for the 31 years from 2062 to 2092. Their respective characteristics are as follows:

A1B: an integrated and unsustainable world, economic growth fast; global population peaks in mid-century and then starts to decline; globalization to reduce regional differences; reduction in regional differences in per capita incomes; balanced in the use of sources of fossil and non-fossil fuels.

A2: fragmented and unsustainable world; maintenance of local identities; continued population growth; economic development oriented regional level; fragmented technological development.

B1: integrated world, local solutions to economic, social and environmental sustainability; consistently growing population, however at lower rates; economic and technological development accelerated and less diverse, oriented towards environmental protection and social equality.

After obtaining the results of dry matter yield (kg ha^{-1}), grain yield (kg ha^{-1}), saccharose yield (kg ha^{-1}), crop water consumption (mm day^{-1}), water irrigation(mm day^{-1}), grain yield per water amount (Kg-grains m^{-3}), saccharose yield per water amount (kg-$C_{12}H_{22}O_{11}$ m^{-3}), statistical analyzes were performed comparing the averages by Tukey method at the 5% probability level, in order to determine if the irrigation management used currently can be applied in future scenarios.

3. Results and discussion

3.1. Climate changes projections

Climate changes projections were made with MarkSim based in the Piracicaba weather with the years 1982–2012. Table 1 shows the average of meteorological variables: maximum and minimum temperature (°C), global radiation (MJ m^{-2} day^{-1}) and rain (mm) for Piracicaba for these years.

The highest values for global radiation, rain and maximum and minimum temperature occurred from October to March which indicates a warm and humid summer. The others months express the cold and dry winter.

November and December were the months which presented the highest values for global radiation (20.17 and 19.60 MJ m^{-2} day^{-1}, respectively). February and March were the months which presented the highest values for maximum temperature (31.02 and 30.41 °C, respectively). January and February were the months which presented the highest values for minimum temperature (19.51 and 19.48 °C, respectively). January and December are the months which presented the highest values for rain (243.65 and 189.99 mm, respectively).

On another hand, May and June were the months which presented the lowest values for global radiation (13.38 and 12.34 MJ m^{-2} day^{-1}, respectively). June and July were the months which presented the

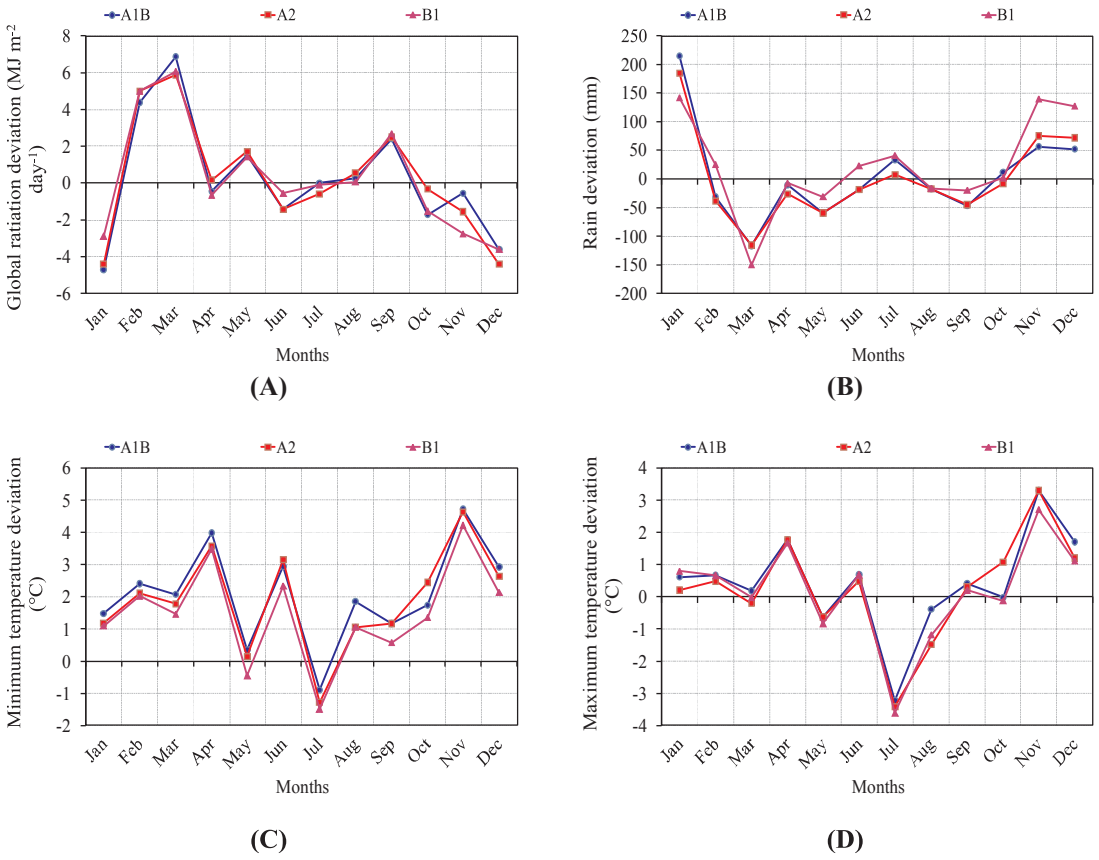

Fig. 1. Average meteorological data deviations of future scenarios (A1B, A2 and B1) for thirty one years (2062–2092) in comparison with current scenario: global radiation deviation (A), rain deviation (B), minimum temperature (C) and maximum temperature (D).

lowest values for maximum temperature (24.41 and 25.72 °C, respectively). Again, June and July were the months which presented the lowest values for minimum temperature (11.06 and 10.69 °C). And July and August were the months which presented the lowest values for rain (33.93 and 30.71 mm).

The highest value of variation coefficient for global radiation presented was in August (16.83%); for maximum temperature was in September (6.52%); for minimum temperature was in July (13.39%) and for rain was also in July (116.65%). This information indicates the weather in winter is more unstable then in summer.

The climate changes projections were obtained after the simulations. Then, it was possible to analyze meteorological data: global radiation, rain, maximum and minimum temperature for thirty one years (2062–2092) for A1B, A2 and B1 scenarios.

Fig. 1 shows the average meteorological data deviations for the three future scenarios for thirty one years (2062–2092). The highest values for global radiation deviation were obtained in March (+ 4.38, + 4.98 and + 4.98 MJ m^{-2} day^{-1} for A1B, A2 and B1 scenarios, respectively). The highest values for rain deviation were obtained in January (+ 215.05, + 184.85 and + 141.35 mm for A1B, A2 and B1 scenarios, respectively). The highest values for maximum temperature deviation were obtained in November (+ 3.30, + 3.30 and + 2.70 °C for A1B, A2 and B1 scenarios, respectively). The highest values for minimum temperature deviation were also obtained in November (+ 4.09, + 4.04 and + 3.54 °C for A1B, A2 and B1 scenarios, respectively).

On another hand, the lowest values for global radiation deviation were obtained in January for A1 B scenario (− 4.70 MJ m^{-2} day^{-1}) and December for A2 and B1 scenarios (− 4.40 and − 3.60 MJ m^{-2} day^{-1}, respectively). The lowest values for rain deviation were obtained in March (− 116.85, −115.25 and −149.95 mm for A1B, A2 and B1 scenarios, respectively). The lowest values for maximum temperature deviation were obtained in July (− 3.22, − 3.42 and − 3.62 °C for A1B, A2 and B1 scenarios, respectively). The lowest values for minimum temperature deviation were also obtained in July (− 0.89, −1.29 and − 1.49 °C for A1B, A2 and B1 scenarios, respectively).

It was expected these deviations caused variations in sugarcane and corn yield in rainfed and irrigated conditions.

3.2. Sugarcane

The three future scenarios are IPCC projections about the climate including changes in solar radiation, temperature and rain. Sugarcane dry matter yield and saccharose yield will be reduced in whatever future scenario under rainfed or irrigated condition (Table 2). One way to compare sugarcane yields for these different scenarios is through the

Table 2
Sugarcane dry matter yield and saccharose yield for the current and the future scenarios in kg ha^{-1}.

Scenario	kg DM ha^{-1}		kg $C_{12}H_2O_{11}$ ha^{-1}	
	Rainfed	Irrigated	Rainfed	Irrigated
Current (1982–2012)	116,923 ^{a*}	136,329 ^{a*}	20,146 ^{a*}	23,557 ^{a*}
A1B (2062–2092)	77,161 ^{c*}	90,384 ^{b*}	13,725 ^{c*}	15,636 ^{c*}
A2 (2062–2092)	79,953 ^{b*}	90,846 ^{b*}	14,296 ^{b*}	15,826 ^{c*}
B1 (2062–2092)	76,776 ^{c*}	88,774 ^{c*}	13,987 ^{bc*}	16,194 ^{b*}

*Superscript letters are an indication of the result of the comparison of averages of columns made by the Tukey test. Values with the same letter are not significantly different at the 5% probability Level.

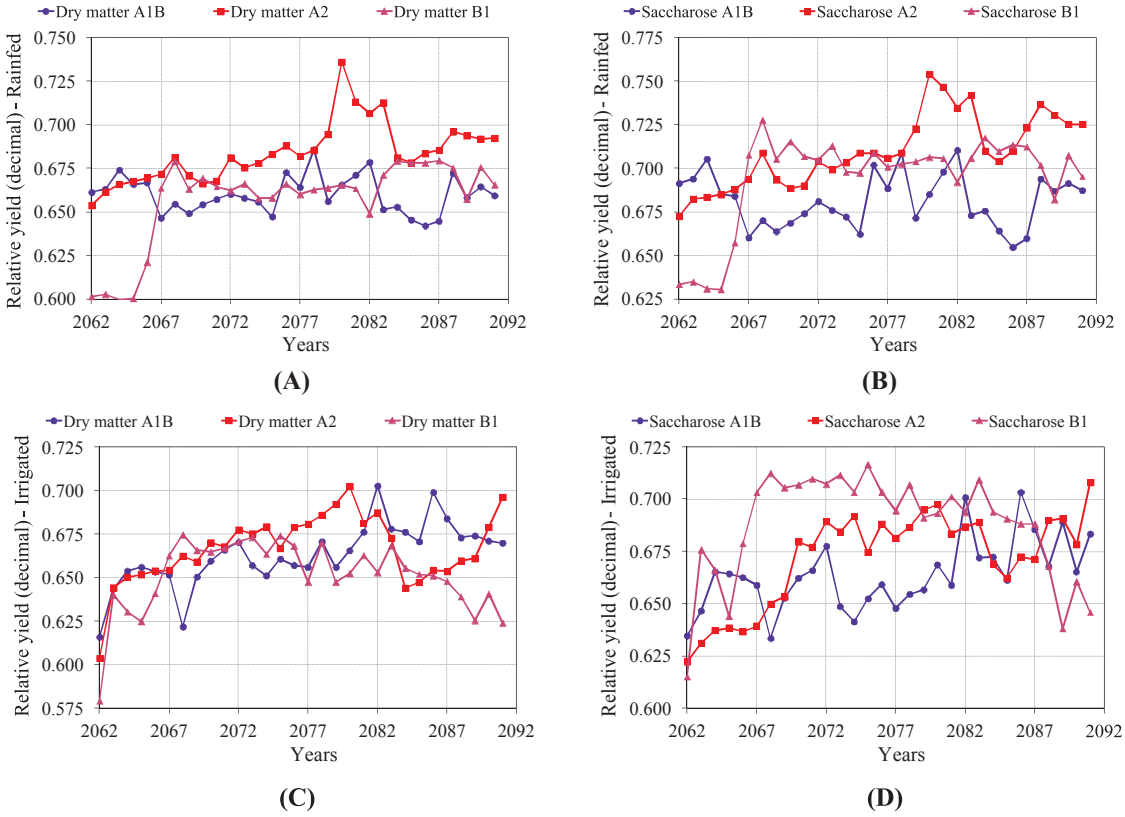

Fig. 2. Sugarcane relative yield under current and future scenarios (A1B, A2 and B1): dry matter (rainfed condition) (A), saccharose (rainfed condition) (B), dry matter (irrigated condition) (C) and saccharose (irrigated condition) (D).

Table 3
Water amount used by sugarcane (mm day^{-1}) and saccharose yield per millimeter of water (kg m^{-3}) used by sugarcane in rainfed and irrigated conditions for current and future scenarios.

Scenario	Rainfed	Irrigated	kg m^{-3} H_2O	
	mm day^{-1}	mm day^{-1}	Rainfed	Irrigated
Current (1982–2012)	3.13 ^{b*}	3.96 ^{a*}	1.23 ^{a*}	1.13 ^{a*}
A1B (2062–2092)	3.16 ^{b*}	3.63 ^{b*}	0.82 ^{b*}	0.81 ^{b*}
A2 (2062–2092)	3.10 ^{b*}	3.57 ^{b*}	0.87 ^{b*}	0.84 ^{b*}
B1 (2062–2092)	3.38 ^{a*}	3.78 ^{a*}	.078 ^{b*}	0.81 ^{b*}

*Superscript letters are an indication of the result of the comparison of averages of columns made by the Tukey test. Values with the same letter are not significantly different at the 5% probability Level.

relative yield indices. These indices are the ratio of future scenarios yield through current scenario yield (Fig. 2).

The dry matter yield of the current scenario under the rainfed condition was 116,923 kg ha^{-1} and the average of the yield for the three future scenarios under the same condition was 77,963 kg ha^{-1}. These numbers led to an average of 66.7% for the relative yield, indicating a 33.3% reduction. This average ranges from 68.3% (79,593 kg ha^{-1}) for the A2 scenario to 65.6% (76,776 kg ha^{-1}) for B1 scenario (Fig. 2A).

The same results were found for the irrigated conditions. The dry matter yield of the current scenario under the irrigated condition was 136,329 kg ha^{-1} and the average of the yield for the three future scenarios under the same condition was 90,001 kg ha^{-1}. These numbers led to an average of 66.0% for the relative yield, indicating a 34.0% reduction. This average ranges from 66.6% (90,846 kg ha^{-1}) for the A2 scenario to 65.1% (88,774 kg ha^{-1}) for B1 scenario (Fig. 2C).

The dry matter yield increased 19,406 kg ha^{-1} in the current scenario when irrigation is used. On the other hand, the dry matter yield increases just 12,038 kg ha^{-1} in average in the future scenarios when irrigation is used.

Likewise, the saccharose yield of the current scenario under the rainfed condition was 20,146 kg ha^{-1} and the average of the yield for the three future scenarios under the same condition was 14,003 kg ha^{-1}. These numbers led to an average of 69.5%, indicating a 30.5% reduction. This average ranges from 70.9% (14,296 kg ha^{-1}) for the A2 scenario to 68.1% (13,725 kg ha^{-1}) for A1B scenario (Fig. 2B).

The saccharose yield of the current scenario under the irrigated condition was 23,557 kg ha^{-1} and the average of the yield for the three future scenarios under the same condition was 15,885 kg ha^{-1}. These numbers led to an average of 67.4%, indicating a 32.6% reduction. This average ranges from 68.7% (16,194 kg ha^{-1}) for the B1 scenario to 66.4% (13,725 kg ha^{-1}) for A1 B scenario (Fig. 2D).

The saccharose yield increases 3411 kg ha^{-1} in the current scenario when irrigation is used. However, the saccharose yield increases 1882 kg ha^{-1} in average in the future scenarios when irrigation is used.

Table 3 shows the water amount used by sugarcane (mm day^{-1}) and the saccharose yield per absorbed water (kg m^{-3}). Sugarcane absorbs 0.83 mm day^{-1} more water when irrigated in the current scenario. However, the saccharose yield decreases 1 kg m^{-3} when irrigation is used in this scenario. In the A1B and A2 scenarios, sugarcane absorbs 0.47 mm day^{-1} more water when irrigated. Moreover, the saccharose yield decreases 0.2 kg m^{-3} when irrigation is used in these scenarios. The only exception is the B1 scenario. It presents the lowest addition in water absorbed when sugarcane is used (0.4 mm day^{-1}) and it presents an increase of 0.3 kg m^{-3} with irrigation.

In the rainfed conditions, the B1 scenario is the one that sugarcane absorbs more water in comparison with others. However, in the irrigated condition the B1 and the current scenario don't differ with 5% probability at Tukey test. On the other hand, saccharose yield per absorbed water is higher in the current scenario (12.3 kg m^{-3} in rainfed condition and 11.3 kg m^{-3} in irrigated condition) when compared with

Table 4
Saccharose Yield (kg m^{-3}) and applied water depth (mm day^{-1}) in sugarcane at different scenarios.

Scenario	Rainfed kg ha^{-1}	Irrigated kg ha^{-1}	mm day^{-1}	kg m^{-3}
Current (1982–2012)	20,146 ^{a*}	23,557 ^{a*}	0.83 ^{a*}	7.9 ^{b*}
A1B (2062–2092)	13,725 ^{c*}	15,636 ^{c*}	0.47 ^{b*}	7.7 ^{b*}
A2 (2062–2092)	14,296 ^{b*}	15,826 ^{c*}	0.44 ^{b*}	6.5 ^{c*}
B1 (2062–2092)	13,987 ^{bc*}	16,194 ^{b*}	0.39 ^{c*}	10.7 ^{a*}

* Superscript letters are an indication of the result of the comparison of averages of columns made by the Tukey test. Values with the same letter are not significantly different at the 5% probability Level.

future scenarios (8.23 kg m^{-3} in rainfed condition and 8.2 kg m^{-3} in irrigated condition) with 5% probability at Tukey test. This probably occurred because sugarcane had its water demand supplied.

In order to evaluate if current irrigation management can be used in the future scenarios to achieve current yield, saccharose yield gain (kg m^{-3}) was compared between the current and the future scenarios (Table 4). The current scenario presents the highest saccharose yield at 5% probability at Tukey test. However, the B1 scenario presents the higher saccharose yield gain (10.7 kg m^{-3}) and the lower water depth (0.39 mm day^{-1}). It means that the B1 scenario features the best environment to sugarcane crop compared with another future scenarios and current scenario with 5% probability at Tukey test.

It is possible to observe the water applied by irrigation decreases while the water consumed by the plant remains the same. This occurred because there is an increase in the amount of water coming by the rain in summer. The B1 scenario has the lowest deviations when rain decreases that is why the water applied by irrigation decrease.

According Fig. 1, there are increases in global radiation (around 5 MJ m^{-2} day^{-1} in February and around 7 MJ m^{-2} day^{-1} in March), in minimum temperature (around 2 °C in February and March) and in maximum temperature (0.5 °C in February and 0.25 °C in March) in the season beginning. This accelerates the crop growing and decreases the water needs. In addition, sugarcane needs water in the season beginning. As the first development stages were shortened, the water needs and the water applied decrease.

On the other hand, there is large rain decrease in February (around 125 mm) which affects the water availability for sugarcane. This fact corroborates with the irrigation necessity to get large yields.

Finally, if the same irrigation management were kept for any future scenarios, there will be around 34% decrease in yield of sugarcane dry matter and 32.6% in yield of sugarcane saccharose.

According to simulations, irrigation won't be an efficient practice to increase saccharose yield in the future scenarios. Yield will be reduced in whatever future scenario simulated. Even though there is irrigation, the yields of future scenarios don't reach in the yield of current scenario. Therefore, the current yield can't be achieved if only the irrigation practice is used.

3.3. Corn

As in sugarcane, corn dry matter yield and grains yield are presented for current and three future scenarios in rainfed and irrigated conditions (Table 5).The relative yield was also used to compare corn yields for these scenarios. The indices are the ratio of future scenarios yield through current scenario yield (Fig. 3).

The dry matter yield of the current scenario under the rainfed condition was 13,929 kg ha^{-1} and the average of the yield for the three future scenarios under the same condition was 8160 kg ha^{-1}. These numbers led to an average of 58.6% for the relative yield, indicating a 41.4% reduction. This average ranges from 64.8% (9020 kg ha^{-1}) for the B1 scenario to 55.4% (7723 kg ha^{-1}) for A2 scenario (Fig. 3A).

On the other hand, the dry matter yield of the current scenario

Table 5
Corn dry matter yield and grains yield for the current and the future scenarios in kg ha^{-1}.

Scenario	kg DM ha^{-1}		kg G ha^{-1}	
	Rainfed	Irrigated	Rainfed	Irrigated
Current (1982–2012)	13,929 ^{a*}	17,772 ^{a*}	4405 ^{a*}	6510 ^{d*}
A1B (2062–2092)	7738 ^{c*}	16,781 ^{c*}	1776 ^{c*}	6931 ^{c*}
A2 (2062–2092)	7723 ^{c*}	17,338 ^{b*}	1698 ^{c*}	7296 ^{b*}
B1 (2062–2092)	9020 ^{b*}	17,910 ^{a*}	2358 ^{b*}	7902 ^{a*}

*Superscript letters are an indication of the result of the comparison of averages of columns made by the Tukey test. Values with the same letter are not significantly different at the 5% probability Level.

under the irrigated condition was 17,772 kg ha^{-1} and the average of the yield for the three future scenarios under the same condition was 17,343 kg ha^{-1}. These numbers led to an average of 97.6% for the relative yield, indicating only a 2.4% reduction. This average ranges from 100.8% (17,910 kg ha^{-1}) for the B1 scenario to 94.4% (16,781 kg ha^{-1}) for A1 B scenario (Fig. 3C).

The dry matter yield increases 3843 kg ha^{-1} in the current scenario when irrigation is used. But, what is different here, the dry matter yield increases 9182 kg ha^{-1} in average in the future scenarios when irrigation is used.

The grains yield of the current scenario under the rainfed condition was 4405 kg ha^{-1} and the average of the yield for the three future scenarios under the same condition was 1944 kg ha^{-1}. These numbers led to an average of 44.1%, indicating a 55.9% reduction. This average ranges from 53.5% (2358 kg ha^{-1}) for the B1 scenario to38.5% (1698 kg ha^{-1}) for A2 scenario (Fig. 3B).

The grains yield of the current scenario under the irrigated condition was 6510 kg ha^{-1} and the average of the yield for the three future scenarios under the same condition was 7376 kg ha^{-1}. These numbers led to an average of 113.3%, indicating a 13.3% increase. This average ranges from 121.4% (7902 kg ha^{-1}) for the B1 scenario to 106.5% (6931 kg ha^{-1}) for A1 B scenario (Fig. 3D).

The grains yield increases 1105 kg ha^{-1} in the current scenario when irrigation is used. However, the grains yield increases 5432 kg ha^{-1} in average in the future scenarios when irrigation is used.

Table 6 shows the water amount used by corn (mm day^{-1}) and the grain yield per absorbed water (kg m^{-3}). Corn absorbs 1.07 mm day^{-1} more water when irrigated in the current scenario. The grains yield increases 1.1 kg ha^{-1} when irrigation is used in these scenarios. In the A1B scenario, corn absorbs 2.28 mm day^{-1} when irrigated and grains yield increases 5.0 kg m^{-3}. In the A2 scenario, corn absorbs 2.23 mm day^{-1} when irrigation is used. However, grains yield increases 6.6 kg m^{-3}. Likewise, in the B1 scenario, corn absorbs 1.95 mm day^{-1} when irrigation is used and grains yield increases 6.0 kg m^{-3}.

In the rainfed conditions, current scenario is different from future scenarios with 5% probability at Tukey test. Likewise, in the irrigated conditions the current scenario is also different from future scenarios with 5% probability at Tukey test. On the other hand, grains yield per absorbed water is lower in the A2 scenario (9.8 kg m^{-3}) when compared with others scenarios with 5% probability at Tukey test. When irrigation is used, grains yield per millimeter of absorbed water is higher in the future scenarios (16.3 kg m^{-3}, in average, for the future scenarios) when compared to current scenario (11.9 kg m^{-3}) with 5% probability at Tukey test.

In order to evaluate if current irrigation management can be used in the future scenarios to achieve current yield, grains yield gains (kg m^{-3}) was compared between the current and the future scenarios (Table 7). The B1 scenario presents the highest grains yield at 5% probability at Tukey test. In the corn crop, the B1 scenario presents the

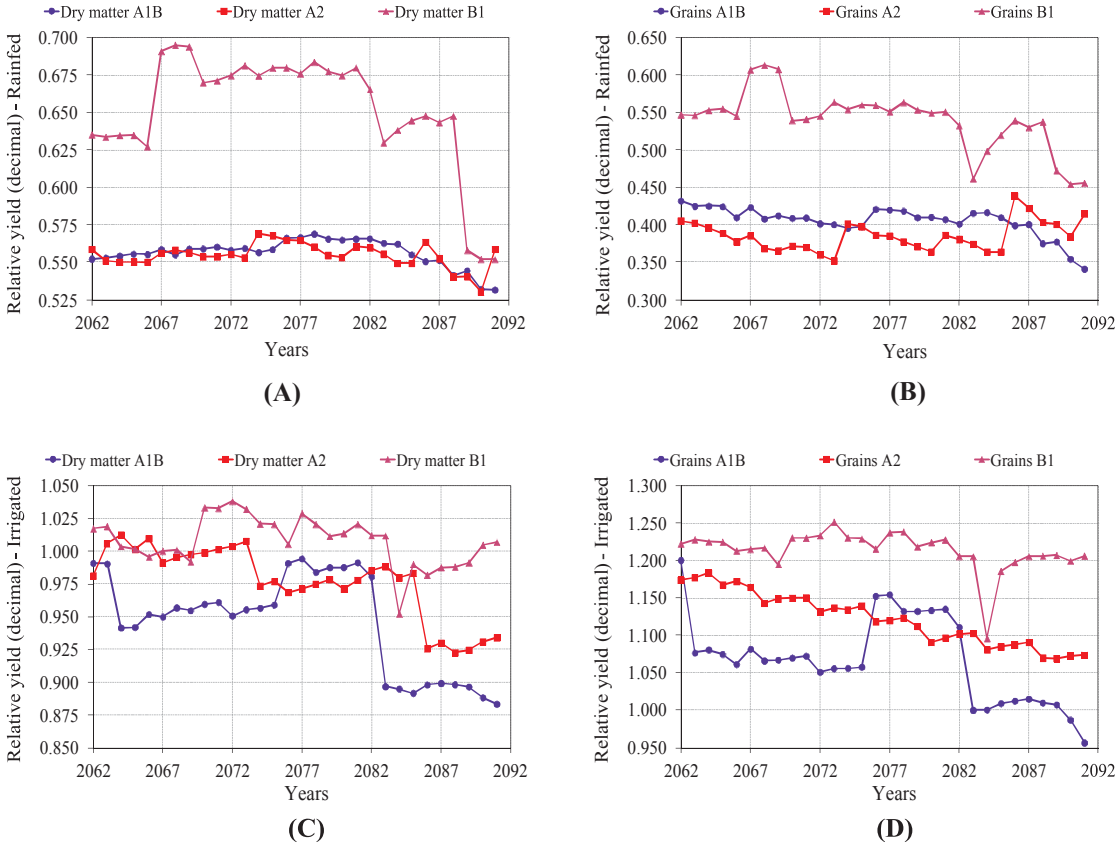

Fig. 3. Corn relative yield under current and future scenarios (A1B, A2 and B1): dry matter (rainfed condition) (A), grains (rainfed condition) (B), dry matter (irrigated condition) (C), grains (irrigated condition) (D).

Table 6
Amount of water used by corn (mm day^{-1}) and grain yield per millimeter of water (kg m^{-3}) used corn in rainfed and irrigated conditions for current and future scenarios.

Scenario	Rainfed	Irrigated	kg m^{-3} H_2O	
	mm day^{-1}	mm day^{-1}	Rainfed	Irrigated
Current (1982–2012)	2.91 ^{a*}	3.98 ^{a*}	10.8 ^{a*}	11.9 ^{c*}
A1B (2062–2092)	1.38 ^{c*}	3.66 ^{b*}	10.7 ^{a*}	15.7 ^{b*}
A2 (2062–2092)	1.44 ^{c*}	3.67 ^{b*}	9.8 ^{b*}	16.4 ^{a*}
B1 (2062–2092)	1.70 ^{b*}	3.65 ^{b*}	10.8 ^{a*}	16.8 ^{a*}

* Superscript letters are an indication of the result of the comparison of averages of columns made by the Tukey test. Values with the same letter are not significantly different at the 5% probability Level.

Table 7
Corn grain yield (kg m^{-3}) and applied water depth (mm day^{-1}) in corn at different scenarios.

Scenario	Rainfed kg ha^{-1}	Irrigated kg ha^{-1}	mm day^{-1}	kg m^{-3}
Current (1982–2012)	4405 ^{a*}	6509 ^{a*}	1.2 ^{c*}	9.7 ^{c*}
A1B (2062–2092)	1776 ^{b*}	6931 ^{a*}	2.3 ^{a*}	18.7 ^{b*}
A2 (2062–2092)	1698 ^{b*}	7296 ^{a*}	2.2 ^{a*}	20.7 ^{ab*}
B1 (2062–2092)	2358 ^{b*}	7901 ^{a*}	2.0 ^{b*}	21.7 ^{a*}

* Superscript letters are an indication of the result of the comparison of averages of columns made by the Tukey test. Values with the same letter are not significantly different at the 5% probability Level.

higher grains yield gain (21.7 kg m^{-3}) and the lower water depth applied (2.0 mm day^{-1}). It means that the B1 scenario, followed by the others future scenarios, the best environment to corn crop compared with current scenario with 5% probability at Tukey test.

Likewise sugarcane, it is possible to observe the water applied by irrigation decreases while the water consumed by the plant remains the same. This occurred because there is an increase in the amount of water coming by the rain in summer. The B1 scenario has the lowest deviations when rain decreases that is why the water applied by irrigation decrease.

Again according to Fig. 1, there are increases in global radiation (around 5 MJ m^{-2} day^{-1} in February and around 7 MJ m^{-2} day^{-1} in March), in minimum temperature (around 2 °C in February and March) and in maximum temperature (0.5 °C in February and 0.25 °C in March). These facts reduce the corn lifetime when occur in season beginning. On the other hand, there is large rain decrease in February (around 125 mm) which affects the water availability for corn. At this stage corn needs water to grow as faster as it can to sustain the flowering around 60 days after the plants emergence. Because of that, irrigation supply the water needs in the corn beggining and decreases the water needs in the entire crop.

4. Conclusion

DSSAT/CANEGRO and CERES-MAIZE were used to simulate sugarcane and corn growth, respectively, under current and simulated future scenarios in Brazil in rainfed and irrigated conditions.

Based on Tukey test at 5% probability, the conclusions are:

1) Sugarcane crop won't present the same dry matter and saccharose yields presented in the current scenario in the future scenarios. The water requirements and the depth of water for irrigation won't change. However, the B1 scenario presents the high saccharose yield per water for irrigation depth, 10.7 kg m^{-3} with 5% probability in Tukey test.
2) Irrigation will help to stabilize sugarcane productivity. It will also be

necessary to explore other techniques such as new cultivar development and adoption of new technologies.

3) Supplemental irrigation will be of vital importance to maintain corn yield. Water should be managed as part of a comprehensive plan for water preservation and rational use.
4) Corn will need high water depths under the future scenarios. On average, 2.2 mm day^{-1} of water will be needed to maintain current levels of corn yield. Currency corn needs 1.2 mm day^{-1}.
5) The models DSSAT/CANEGRO and CERES-MAIZE are suitable tools for studying the performance of crops under future climate scenarios. The MarkSim model is also of importance, as it can be used to provide input climate data, for future scenarios indicated by the IPCC, for both models.
6) This research is only a small part of major study about yield using crop growth modeling. It will be necessary to carry out more studies with future weather conditions, using different varieties or hybrids of crops, and compare the modeled results with current data from farms.

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